Countermine Operations in Very Shallow Water and Surf Zone: The Role of Bottom Crawlers

Tony Aponick
Foster-Miller, Inc.
350 Second Ave.
Waltham, MA 02451
TAponick@foster-miller.com

Chuck Bernstein
NSWC – Coastal Systems Station
6703 W. Hwy. 98
Panama City Beach, FL 32407
bernsteincl@ncsc.navy.mil

I. COUNTERMINE MISSION OVERVIEW

In littoral warfare, strategic, operational and tactical mobility is an obvious advantage to naval forces that rely on unobstructed sea lanes. Naval mines can diminish or deny this advantage by reducing freedom of maneuverability and preventing naval forces from controlling or shaping the battlefield.

In the Surf Zone (SZ) region, small autonomous crawling robots are being developed by the Office of Naval Research to perform mine hunting missions in support of the Mine Countermeasures (MCM) task force.

II. CRAWLER OVERVIEW

The modern history of military seagoing crawling robots begins about 1990 with a DARPA program called Lemmings. The objective of the effort was to minimize the danger of landing marines on a mine-protected beach. This is not an easy problem – mines are extremely lethal, easy to deploy and very difficult to find and defeat. One needs to find and defeat ALL of them!

A. The Lemming Class

The idea behind Lemmings was simple: Each crawler was equipped with a sensor that could find manmade objects. Fifty to 100 crawlers were released into the landing zone and they would wander around the area (underwater). When a crawler found such a target object, it would stop and snuggle up to it. At a pre-arranged time or on receipt of a pre-arranged signal, each successful crawler would detonate an onboard charge of 4 to 7 lb of high explosive, removing both itself and the mine from any further consideration. Fig. 1 shows a Lemming snuggled next to a SZ mine. In Fig. 2, the whisker sensor can be seen that found minelike objects by rubbing against them and listening to the sound made by the rubbing. Rocks sound very different from mines – or so the theory went at the time.

Fig. 1. A Lemming class crawler near a surf zone object.

Fig. 2. A Lemming and its sensing whisker

As is always the case in the evolution of an idea, many, many different approaches to the crawler defeat of SZ mines were tried, and the platforms proliferated. Many other uses for crawlers were thought about and implemented – some of them are in current use. Foster-Miller's own little family of seagoing crawlers is shown in the portrait of Fig. 3, taken about 1995.

B. The Tactically Adaptive Robot (TAR) Class

As a result of the continuing evolution, it became clear to the Navy that a lot more capability could be asked from seagoing crawlers than was being asked from the simple Lemmings. Further, the warfighters made it clear to the R&D community that the deposition of a large number of additional

0-933957-31-9

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 SEP 2003**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Countermine Operations in Very Shallow Water and Surf Zone: The Role of Bottom Crawlers**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Foster-Miller, Inc. 350 Second Ave. Waltham, MA 02451**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM002146. Oceans 2003 MTS/IEEE Conference, held in San Diego, California on September 22-26, 2003. U.S. Government or Federal Purpose Rights License., The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Fig. 3. The crawler family ca 1995.

bombs into a beach landing area infested with mines was not an approach that was ever going to be used in practice.

The response was the initiation of the ONR Very Shallow Water/Surf Zone Mine/Countermine program – a program in which the development of a more advanced class of crawlers played a significant part. As implemented in this effort, the TAR class vehicles were equipped with a variety of instrumentation for finding and verifying munitions emplaced near the beach, navigation systems for knowing where they were in real time, and communication systems over which they could receive mission direction and forward data and imagery about the undersea situation. The notional mission for these platforms was (and still is) to reconnoiter potentially desirable locations for beach landings, to covertly communicate status to the mission commander, and to (if directed) neutralize the mines that are in the way of the landing, confirming their safe removal.

A platform we designed and built for this mission concept is shown in Fig. 4. It is almost twice as large as a Lemming and carries more electronics, both for command and control and as infrastructure for various instrumentation suites

Fig. 5 shows the TAR platform in more detail. It carries a modular Sensor Processor box (Fig. 6) on its top deck into which a whole spectrum of compatible instruments can be plugged (further discussed in Section III). The sensor processor interoperates flexibly with the electronic controls of the platform mounted inside the vehicle. Fig. 7 shows an instrument-equipped TAR at sea.

The TAR experiments are conducted from a beach-based command center. All command and control inputs for the vehicle and all real-time data related to the instrumentation are conducted along a tether which goes from the vehicle to a surface float, and from the float to the beach over RF. The float, shown in Fig. 8, carries its own control box containing the needed radios and translators, and antennas for multiple channels

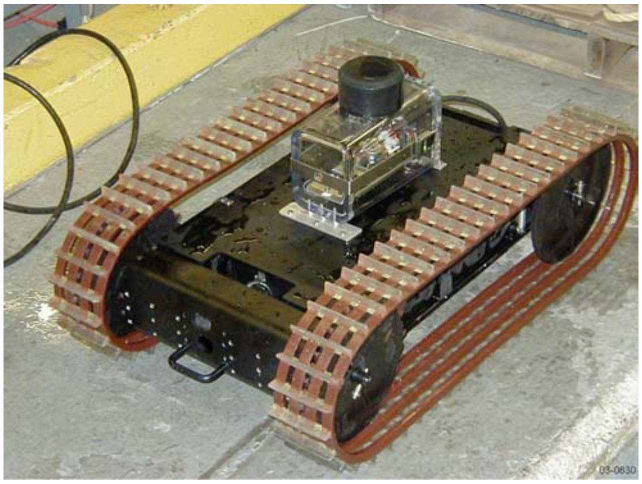


Fig. 5. TAR portrait.

Fig. 4. A TAR class robot in the surf.

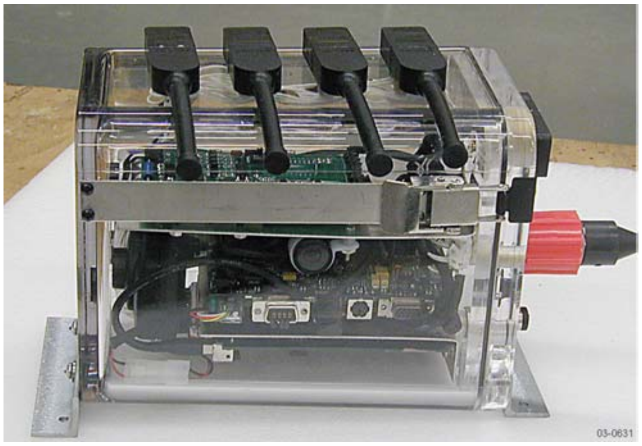


Fig. 6. The TAR sensor processor.

Fig. 7. The TAR at sea.

Fig. 8. Sea TAR float.

C. The SeaTALON Class

In parallel with Navy efforts, small crawling robots were becoming a subject of intense investigation by the Army and Special Operations communities for surface use. The principal jobs for which they were enlisted included Explosive Ordnance Disposal (i.e., cleaning up mines and munitions after warfare so people can return to their normal lives) and Intelligence, Surveillance, Reconnaissance (ISR) work – the remote gathering of information by an essentially expendable platform. Very rugged platforms were being designed by a number of companies to answer these operational needs, and in about the 2001/2002 timeframe the Navy decided to take advantage of these developments by borrowing the technology and starting a new generation of VSW/SZ countermine platforms. Where the TAR platforms were highly flexible tethered research vehicles capable of carrying broadly various kinds of instruments on their backs or around their periphery, the new SeaTALON class (Fig. 9) was conceived at the outset to be a fleetworthy, deployable platform carrying most instruments internally and capable of communication of all command and control and data streams over a sonar link. Two sonar base antennas are to be used in a long baseline configuration so as to provide navigation in addition to communication.

The land-based Talon vehicle, on which the SeaTALON is based, is in current service in former Yugoslavia, Afghanistan and Iraq – this is not R&D (see Fig. 10).

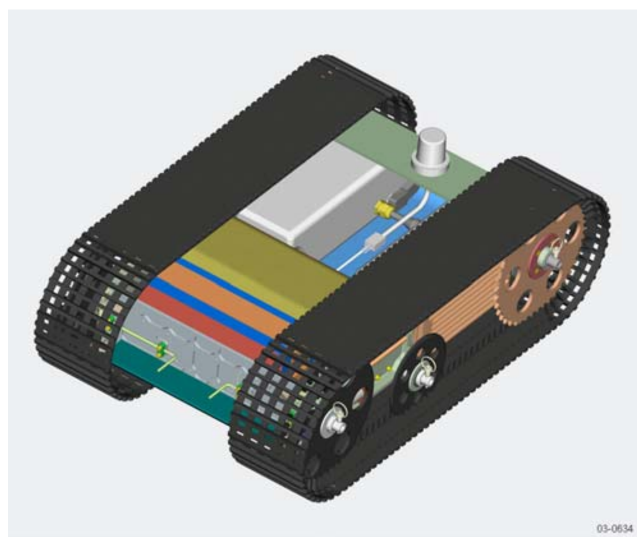


Fig. 9. Schematic view of the SeaTALON – sonar transducer mounted aft (upper right).

Fig. 10. Land-based Talon on ISR duty in theater.

Work on the crawler platforms and the SZ/VSW countermine mission is in current progress on two main fronts – the SeaTALON platform and the associated sonar system is being implemented (Fig. 11) and thoroughly tested in a progression of field tests and exercises, and the needed countermine sensors and imagers are being developed (Section III) and put into configurations suitable for installation on the SeaTALON and use by the fleet.

III. MINE/COUNTERMINE INSTRUMENTATION

Because both Reacquire/Identify/Neutralize (RIN) and exploratory missions are of prime interest, the goal has been to develop a sensor suite that provides a basic mine-like object detection and identification (ID) capability. Given the low speed and limited channel address ability available in through-water communication channels, we are also seeking a capability to autonomously discriminate between mine-like and non-mine-like targets, and thereby reduce the need to communicate with the system operator when false targets are encountered.

Fig. 11. Two SeaTALONs in a surf exercise.

Target detection must provide a reasonable area coverage rate compatible with the crawling platform and its on-the-bottom environment. The initial goal for (ID) imaging is to provide an image for a human operator under all likely environmental conditions.

A. Optical Imagery

Initial efforts have applied conventional low-light grayscale cameras to obtain target images suitable for human operator-based target identification. The cameras are typically used at very short ranges (<2m) for target identification. Inexpensive cameras from Mini-Circuits and even web-cam type cameras have been used (Fig. 12), some with illuminators. The quality of the images is strongly dependent on ambient lighting and water optical conditions, as the examples show.

CSS is developing an enhanced camera system that will adapt to the optical conditions at hand. In good conditions, the camera will be employed in the standard fashion. If backscatter is moderate or the ambient light is too low, a bistatic illumination technique will be applied to reduce backscatter. In severe conditions, a scanning laser will be used to further reduce backscatter and improve the image. The scanning technique has been shown to image objects at up to much longer ranges in murky water. Under these test conditions, a standard camera image would not clue a human observer that a target was present (see Fig. 13).

An additional advantage of the laser scanning technique is that it can generate a range map of the target space. The range map contains information about the size and shape of target objects directly, and can thereby facilitate autonomous onboard target discrimination and ID in the future.

Under a grant from ONR, Dr. Truong Nguyen of the University of California at San Diego has developed wavelet-based compression techniques for still images. The UCSD effort coded a compression algorithm for our target Sensor Processor (SP), a Pentium III based data acquisition computer. Camera images have been successfully captured, compressed, and transmitted over the acoustic channel. The acoustic modems are the Benthos ATM885 Telesonar modems, which are capable of 600 and 1200-baud transmissions in the VSW over 1 to 2 km, depending on acoustic conditions.

Real-time video has also been used on the crawlers. Video is typically transmitted from a radio utility float using low power L-band transmitters. CSS is investigating video compression algorithms that would provide low rate video that could be packed into the command/control data channel.

B. SONAR Imagery

Sonar systems have been used on the crawlers to provide greater area coverage rates than can be obtained using contact

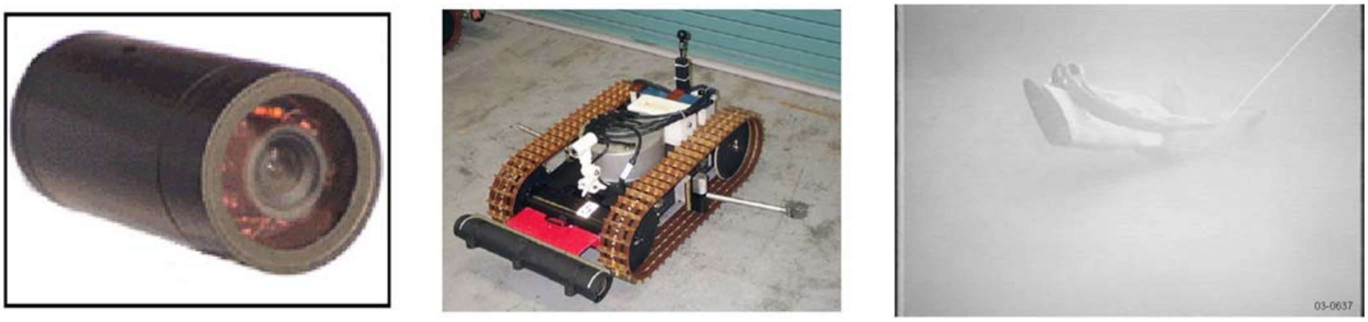


Fig. 12. Left: Low light lipstick camera. Center: TAR crawler outfitted with camera. Right: Image of rifle butt taken using onboard camera from TAR vehicle.

Fig. 13. Enhanced camera system development effort. Left: Conventional flash image of test target taken at night. Center: Grayscale image using bistatic illumination to reduce backscatter. Right: 2D rendering of range map of pipe cap target from laser scanning technique.

or tactile sensors. Side scan sonars have been used, and more recently, mechanically steered, rotating head sonars have been applied. The rotating head sonar pans a single narrow beam in a circular pattern using a motorized mount in the sonar head. For each ping, the sonar returns a frame of data indicating energy levels for a series of range bins. The plotted data indicates reflective targets in the space surrounding the vehicle (see Fig. 14).

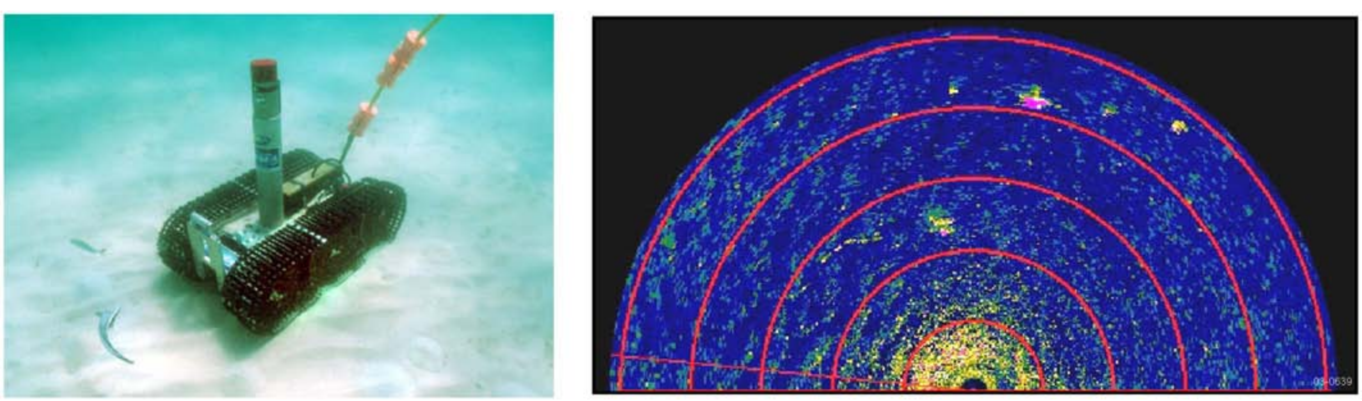


Fig. 14. Rotating head sonar mounted on TAR crawler during reacquisition exercises and an example of a half field scan. Range lines are 10m per division. Five targets are visible in the scan.

Typical useful ranges in the VSW are between 25 and 80m, depending on depth and sea state. The maximum range is limited by the shallow ceiling, which creates a strong surface reverberation, and also by bottom reverberation. In high sea states rough seas, the performance is degraded, but we can improve the images by lowering the sonar operating frequency and reducing the maximum scan range. Under mild conditions, the sonar will scan a 40m radius (>5000 m^2) circle in about 20 sec.

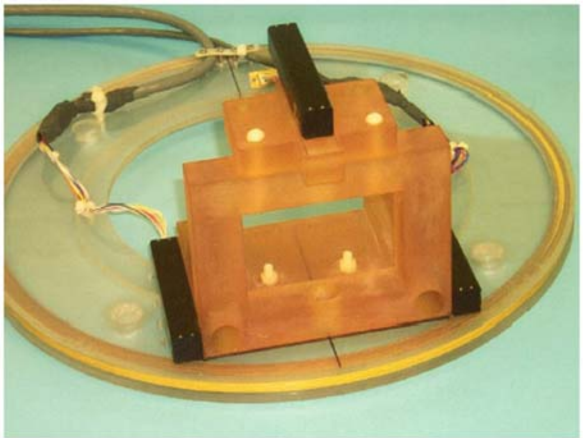
For minefield exploration, a raster search pattern is planned containing a series of scan points. For target reacquisition, outward spiraling search paths are generally used, beginning at the reported contact point and progressing outward. The scan points are designed so that the sonar images will overlap and achieve full area coverage.

CSS recently acquired a Dual Frequency Sonar (DIDSON), which is built by the Applied Physics Laboratory of the University of Washington. This is a lens-based imaging sonar that operates at 900 and 1,800 kHz. The DIDSON is useful for imaging targets at near contact to about 30m range (see Fig. 15).

C. Other Sensors

Various other sensors have been applied to enable the crawlers to detect and classify targets on the sea floor. These have included tactile and chemical sensors. CSS has been developing new sensors specifically for the crawler application, including an enhanced 3D camera system for target, a short baseline magnetic gradiometer, a mechanical impulse response sensor, and a simple bumper-collision sensor. An ONR-supported grant to Dr. Chris Rahn of the Mechatronics Research Laboratory at Pennsylvania State University is developing mechanical-tactile imagine systems for target in environments unsuited to sonar or optical imaging (see Figs. 16, 17 and 18).

Fig. 15. Dual Frequency Sonar (DIDSON) mounted on TAR crawler top plate.



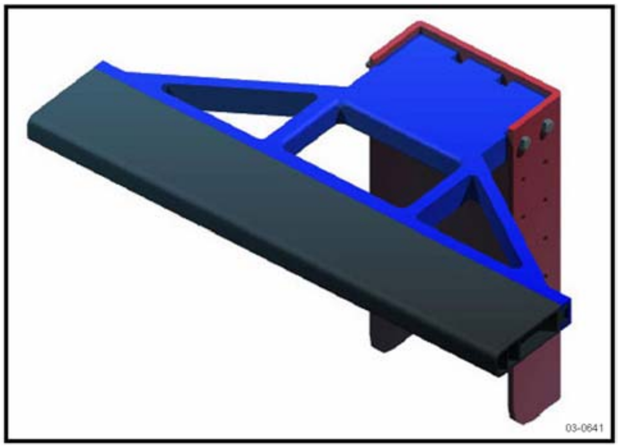


Fig. 16. Left: Magnetic gradiometer prototype constructed using 3-axis fluxgate magnetometer and accelerometer units. Right: New bumper prototype. The bumper is connected directly to the vehicle controller to stop the vehicle immediately if it encounters an impassible obstacle.

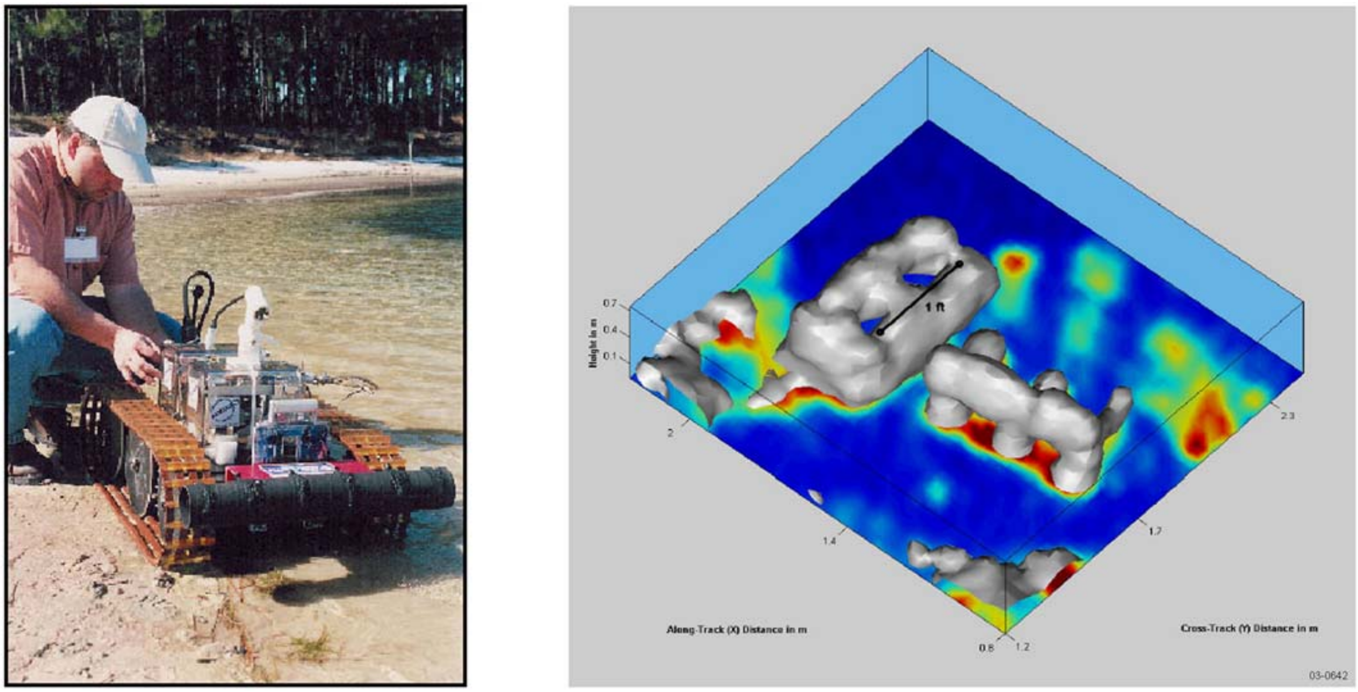


Fig. 17. Left: TAR crawler with first generation TNT/DNT chemical sensor from Nomadics, Inc.
Right: Rendering of a cinderblock target from the APLUW developmental blazed array scanning sonar.

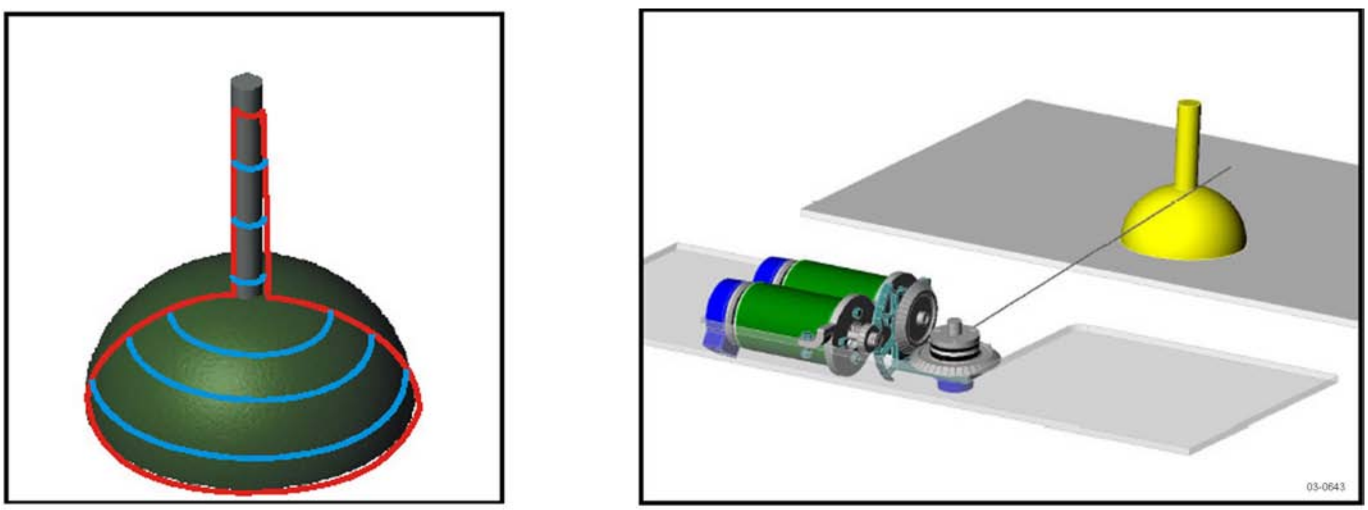


Fig. 18. Left: Flexible whisker-based shape tracing (mechanical imaging) concept being pursued under an ONR grant to the Mechatronics Research Laboratory at the Pennsylvania State University. Right: The active, motorized hub is instrumented with torque, force, and position sensors. The entire mechanism can be tilted out of plane to generate 3D images of the target.

IV. OPERATIONAL IMPLEMENTATION

A. TAR Mission Results

The most significant demonstration to date was the application of the TAR robots during the Autonomous Unmanned Vehicle Fest (AUV Fest) in October 2001. In that event, the TAR robots were outfitted with acoustic modems, magneto-inductive receivers, metal detector, and contact-tactile sensors to demonstrate through water communications for command and control as well as transmission of image data sets. During the Fest, the crawlers successfully demonstrated reacquisition of pre-surveyed targets and

image-based ID of those targets. Detection was based solely on bumper and tracer-contact sensors at that time. We also demonstrated using DARPA-developed Sea Web 2000 acoustic modem networking software to relay commands and data (an image) through an intermediate crawler (see Figs. 19 and 20).

Recently, CSS participated in the Defense Threat Reduction Agency-sponsored event titled Comprehensive Hazmat Emergency Response Capabilities Assessment Program. The event simulated a terrorist attack on an ammonia barge in port, and various unmanned vehicles were used to collect forensic evidence around the site. The TAR crawlers were used in two configurations, with DIDSON and camera, and with rotating head sonar and camera (see Figs. 21 and 22).

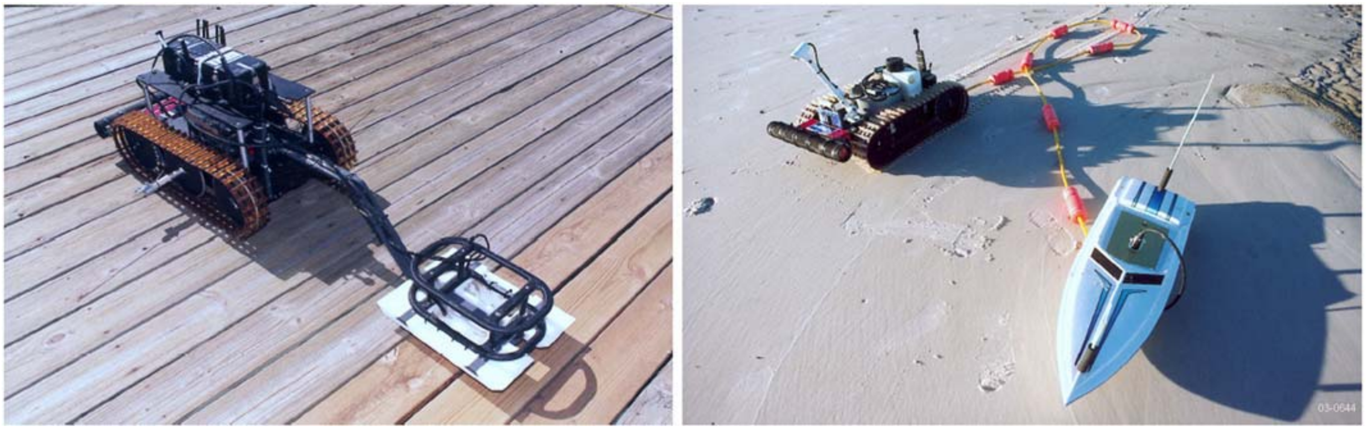


Fig. 19. TAR configurations used during UUV Fest 2001. Left: TAR with cameras, shape tracers, bumper, and Pulse Eddy Induction Coil (PEIC) metal detector. Right: Reacquisition configuration TAR with camera, bumper, acoustic modem and surface RF communications float.

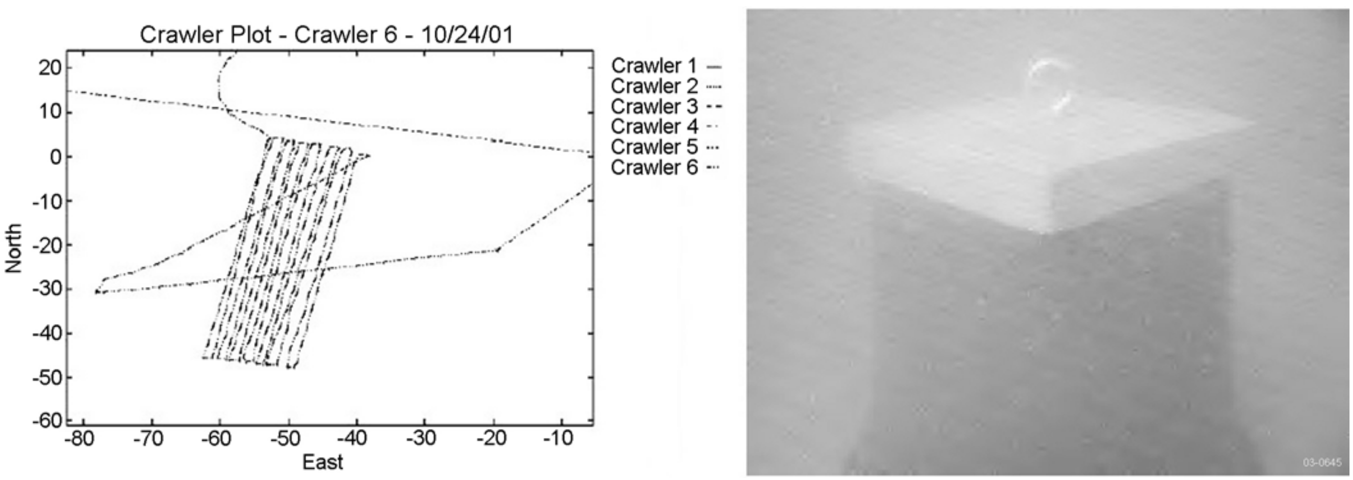


Fig. 20. Left: Plot of autonomous raster search of a test field during AUV Fest 2001. Right: Located target image. The target was detected using the bumper and the camera image was compressed 50:1 using the UCSD-developed compression codes. The image was then transmitted at 1200 baud using the Benthos ATM885 telesonar modem to an RF buoy, which relayed the image to the Operator Control Station (OCS), where it was decompressed and displayed.

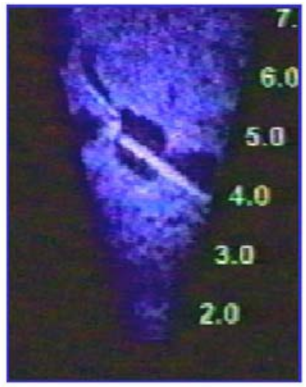



Fig. 21. Left: TAR with DIDSON and camera configured for the DTRA CHERCAP exercise in February 2003. Middle: DIDSON image of object located during test. Right: Camera image of the same object.

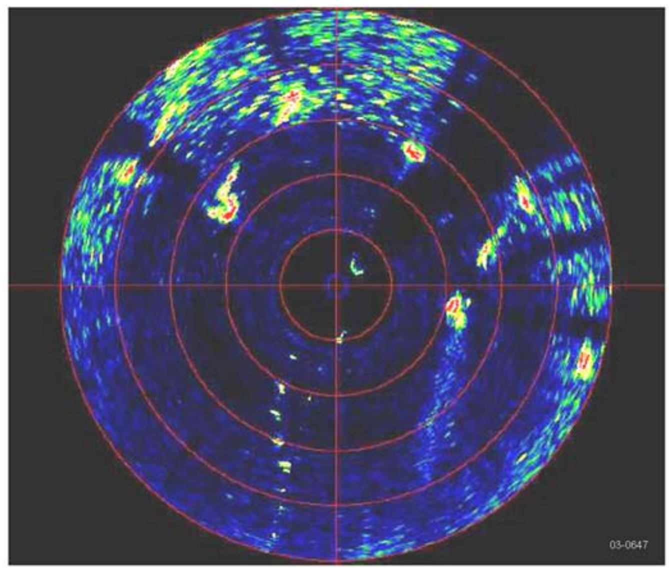



Fig. 22. Left: DTRA CHERCAP TAR configured for rotating head sonar and camera operation. Right: Sonar view of the surrounding fuel depot pier.

Since the rotating head sonar has been added to the sonar suite in the TARs, we have demonstrated reacquisition of targets based on overlapping sonar scans. During tests in the Gulf of Mexico in December 2002, we successfully located and imaged test targets using the sonar. Software tools are under development for the Operator Control Unit (OCU) to facilitate operator-based marking of suspicious targets in the sonar scans, and to facilitate automatic scripting of the robot to revisit and any anomalies that were found.

Ultimately, we will have a sensor suite for exploratory or reacquisition missions that will be a bolt-on package for the TARs or fully integrated into the new Sea Talon Vehicles. The suite will include a sensor processor, search sonar, imaging system for ID, and possibly a magnetic gradient sensor or chemical-explosive material sensor.

B. Sonar Communications/Navigation

The subsea crawlers require a communication link to provide a channel for command and control data from and data from the various sensors to a supervisory location typically located onshore. ONR has invested significant resource in the development of sonar systems for this purpose. Typical long-baseline navigation systems use the same frequency band as acoustic communication systems, and thus it is both logical and convenient to merge both navigation and communications systems into one set of hardware. This removes interference that occurs when the two systems are operated asynchronously, and provides a savings in payload space and power. We are using the Woods Hole Oceanographic Institution (WHOI) Micro Modem system described in detail in [1]. Navigation and communication modes suitable for both single vehicles and large groups have been developed, allowing the use of the

same fixed nodes for different types of vehicles (swimmers and the crawlers) within the same net (see Fig. 23).

Briefly explained, the operation of the Nav/Comm sonar system is simple. Two transponder buoys are deployed on a long baseline in the operating area. The transponders respond to navigation queries by emitting a return ping, facilitating time of flight measurement. A communications buoy is also deployed at a convenient point. The communications gear consists of a micromodem with transducer, processing electronics, and a relaying RF transmitter to facilitate communications with the onshore base of operations. The crawler itself is equipped with a corresponding MicroModem and transducer capable of working with both the communications and navigation buoys. The operating layout is shown schematically in Fig. 24. The characteristic size of the operating area is presently about 1 km square – we are working intensively with WHOI to double this range – not a trivial task in the sonar-unfriendly surf zone.

C. SeaTALON Status

The SeaTALON platform design has been completed and two vehicles have been built. A series of shakedown tests are underway to ensure reliable operability and the ability to carry the needed countermine instrumentation in realistic environments. The Nav/Comms sonar has been tested in operation and its ability to interoperate with a variety of swimmers in both VSW and the SZ has been demonstrated. The next major steps will be to integrate the instrumentation on the platform (cameras, imaging sonar and physical bumper) in working situations and following up with an increasingly challenging series of demonstrations and fleet exercises (Section V).

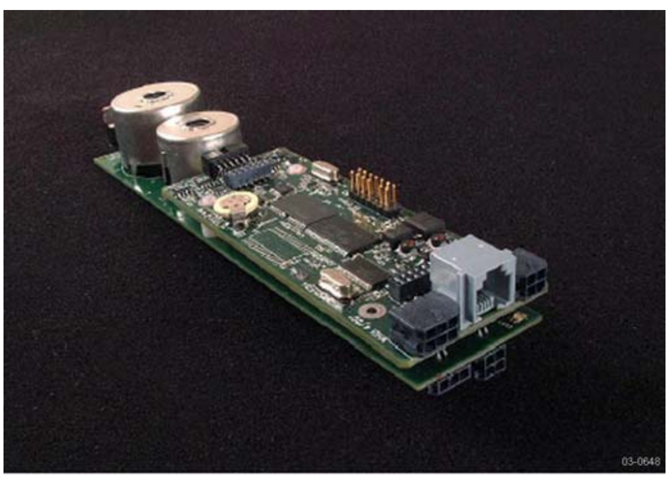


Fig. 23. WHOI MicroModem – accompanying transducer is easily seen on vehicle in Fig. 9.

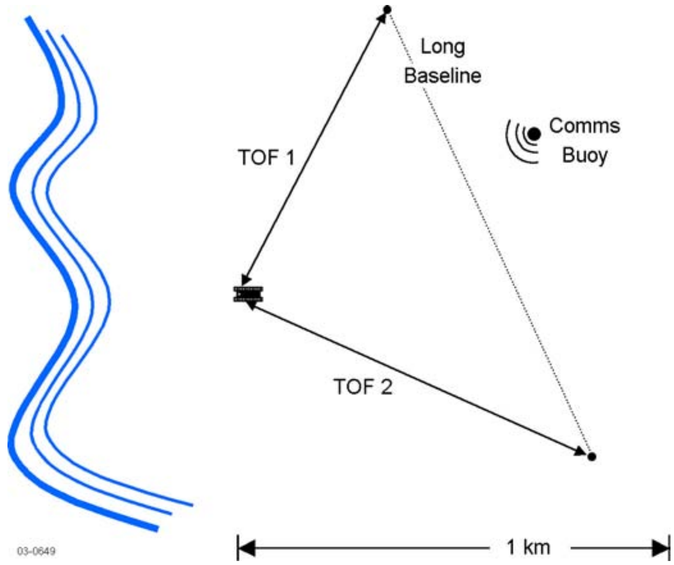


Fig. 24. Navigation/communication sonar deployment.

V. FLEET DEMONSTRATIONS AND TRANSITION

The next major demonstration of the SZ Robotics platforms will take place during a fleet exercise to be conducted during 2004. This demonstration will involve coordinated Mine-Countermine missions among various swimming and crawling unmanned systems. Several work-up exercises will be held at various locations leading up to the demonstration.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Tom Swean and the Office of Naval Research for their support and funding of this research.

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[1] L. Freitag, M. Johnson, M. Grund, S. Singh and J. Preisig, “Integrated Acoustic Communication and Navigation for Multiple UUVs” in *Proc. Oceans 2001*, Honolulu, Nov. 2000.